The Potential of Phased Arrays for Planetary Exploration

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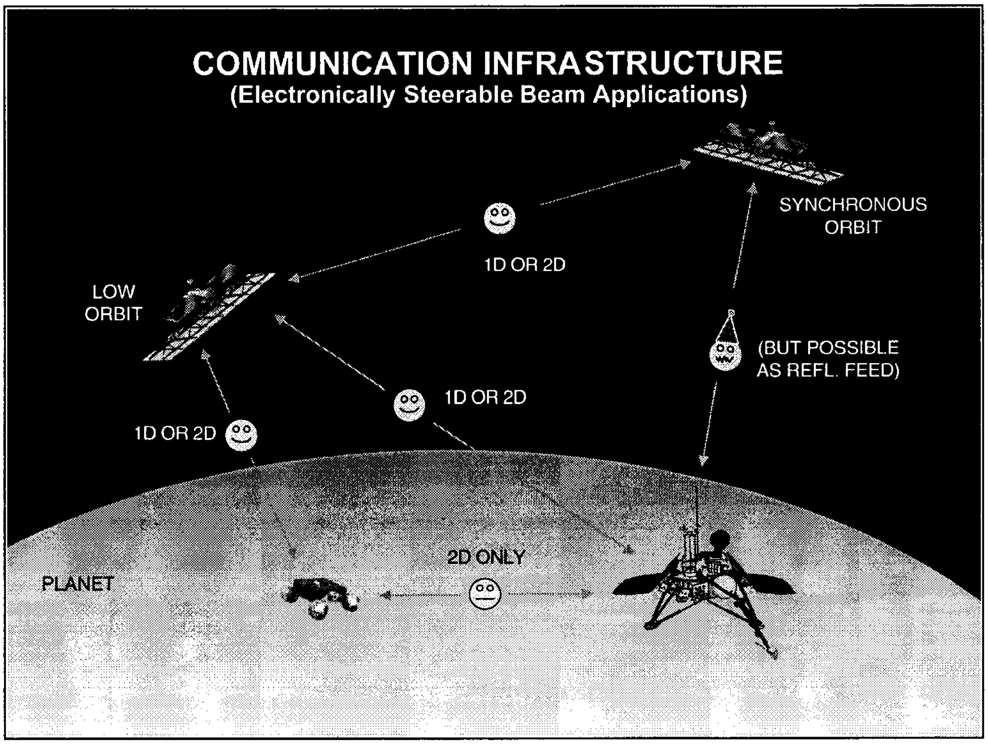
Phased array antennas provide steering of high gain beams at electronic speeds. Such beams appear to offer the prospect of high data rate communications in planetary exploration scenarios. However, phased arrays are by no means a panacea. Moreover, the current state of the art is such that the cost of such antennas is prohibitive for this application due to both their complexity and their mass. Recent advances in the design of phased arrays have led to a revival of interest in their use. This paper examines their potential for communications in planetary exploration.



This is an artist's concept of the kind of connectivity envisioned for planetary exploration. We consider, as an exemplar, the Mars Communications Infrastructure planned for development during the next decade. This infrastructure will involve links among planetary orbiters in both stationary and low orbits, landers, and rovers.

So Why Don't We Use Phased Arrays?

- They are complex and expensive.
- They are overkill in some instances.
- They are massive.
- Large apertures require *many* radiating elements.
- Multiple frequencies (if needed) may require multiple apertures.

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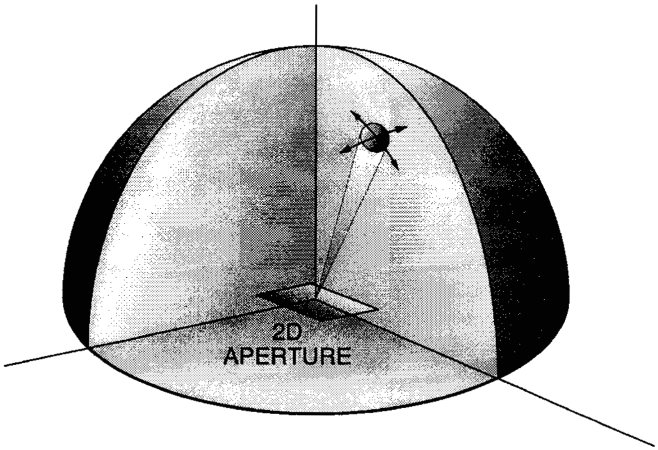
Phased arrays have not been widely considered for space exploration because they are complicated and thus expensive. Also, they provide capabilities that are of dubious value in some applications such as deep space to earth links where wide angle steering at electronic speeds are not necessary. They tend to be massive by virtue of their complexity. If high gain is desired, a large aperture is required and this aperture must be filled with closely spaced radiating elements. Moreover, design of such an aperture for multiple frequencies is problematic primarily because the electrical spacing between the elements is a critical design parameter, which, of course varies with frequency.

PENCIL BEAM (HIGH GAIN)



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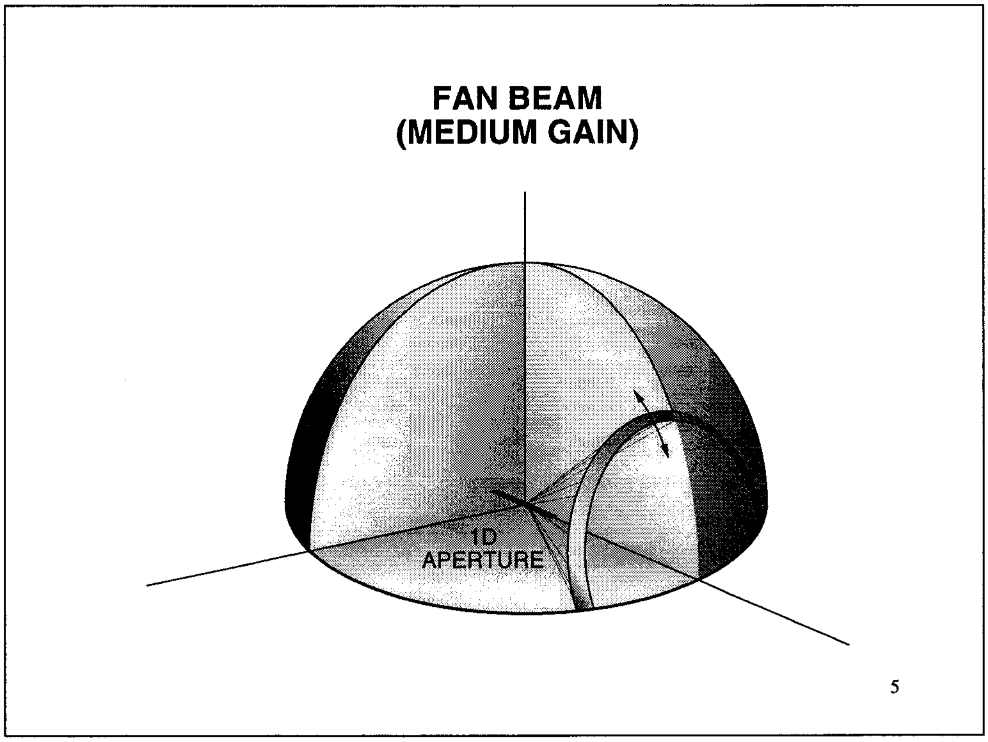
To begin with, let us review the sort of beam radiated by a two-dimensional aperture. Such an aperture concentrates the radiated energy in two dimensional producing a "pencil" beam that is usually elliptical in shape, a special case being a circular spot beam.



A one-dimensional aperture produces a "fan" beam which, as can be seen here is not really fan shaped at all. It is in fact conical. An interesting consequence of this is that the antenna array factor exhibits no scan loss for reasons which will become clear in a moment.

Intuitive Gain Formulas

(Two Dimensional Apertures)

$$Beamwidth = \frac{1}{D_\lambda \cos\theta} \times \frac{1}{D_\lambda} \qquad Spot\ Area = \frac{1}{D_\lambda^2 \cos\theta}$$

$$Gain = \frac{4\pi}{Spot\ Area} = \frac{4\pi D_\lambda^2}{\cos\theta} = 4\pi A_{\lambda;proj}$$

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In order to assess the applicability of phased arrays in a given link scenario, it will be important to be able to quickly estimate their gain, beam width, aperture size, and number of elements. Here we present a very simple and intuitive set of admittedly approximate formulas relating these parameters. (If you are an antenna engineer, this would be the time to go out for coffee!) The antenna gain derives from the concentration of the radiated energy into a beam. The degree of concentration can be measured by the ratio of the spot area to the area of a sphere (in Steradians). The size of the spot is inversely proportional to the aperture size. The aperture in question is the aperture area projected in the direction of the beam and theta is the angle between the beam direction and the normal to the physical aperture. This provides a very simple approximate formula for the gain.

Simple Formulas

(One Dimensional Apertures)

Linear Aperture with Isotropic Elements:

$$Beamwidth = \frac{1}{L_\lambda \cos\theta} \qquad Spot\ Area = \frac{2\pi}{L_\lambda}$$

$$Gain = \frac{4\pi}{Spot\ Area} = 2L_\lambda = \frac{2M\left(\frac{\lambda}{2}\right)}{\lambda} = M$$

If on a ground plane: $Gain = 4\,L_\lambda = 2\,M$

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The preceding reasoning can also be applied to a one-dimensional aperture filled with isotropic radiators. (While isotropic radiators do not exist, this is a good approximation provided the elements radiate isotropically over the angles covered by the high gain beam.) Here again the beamwidth is inversely proportional to the projected aperture. Note, however, that the total spot area is independent of the beam angle which results in the previously mentioned absence of scan loss. If the antenna radiates into a hemisphere by virtue of being place over a ground plane, the gain is doubled.

Simple Formulas - Continued

Array of isotropic line sources:

$$Gain = \frac{\pi}{Beam\,Width} = \pi L_\lambda \cos\theta = \tfrac{1}{2} kL \cos\theta$$

If over a ground plane:

$$Gain = kL\cos\theta = 2\pi L_\lambda \cos\theta = \pi N \cos\theta$$

So, for a rectangular array of isotropic line sources with half wavelength spacing, over a ground plane:

$$Gain =$$
$$Gain\ of\ M\ element\ linear\ array \times Gain\ of\ array\ of\ N\ lines$$
$$= \pi MN \cos\theta = 4\pi A_{\lambda;proj}$$

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Finally, consider a finite array of parallel infinite line sources over a ground and parallel to it. Using our approximate method, it is seen that the gain is pi times the number of elements (assuming half wavelength spacing) times the cosine of the scan angle. Now, if each line source is a finite one-dimensional array of isotropic sources, the gain of the resulting two-dimensional aperture is the product of the gain of the line source array and that of the linear array; that is, pi times the number of elements leading to the by now familiar formula for the gain of a uniformly illuminated aperture radiating into a half space.

Linear Apertures

One Dimensional	Aperture Size in Centimeters			Other Attributes	
Gain in dB	S-Band	X-Band	Ka-Band	Number of Elements	Beamwidth in Degrees
10	50	9	2.5	5	23
20	500	90	25	50	2.3
30	5000	900	250	500	0.23
40	50000	9000	2500	5000	0.023
50	500000	90000	25000	50000	0.0023

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The previously derived simple approximate formulas may now be used to produce a table of the attributes of candidate apertures for planetary use. Such a table, computed for one-dimensional apertures, is shown here. The gain determines the electrical aperture size, the beamwidth, and the number of elements while the frequency determines the physical size of the aperture. The green areas denote practical configurations while the red indicates designs deemed prohibitive in one or more aspects. We conclude that agile fan beams with gains in excess of 20 dB are probably not practical.

Rectangular Apertures

Two Dimensional Gain in dB	Aperture Size in Centimeters			Other Attributes	
	S-Band	X-Band	Ka-Band	Number of Elements	Beamwidth in Degrees
10	10.8 × 10.8	3.3 × 3.3	0.9 × 0.9	4	64
20	36 × 36	11 × 11	3 × 3	36	20
30	108 × 108	33 × 33	9 × 9	324	6.4
40	360 × 360	110 × 110	30 × 30	3136	2
50	1080 × 1080	330 × 330	90 × 90	32400	0.64

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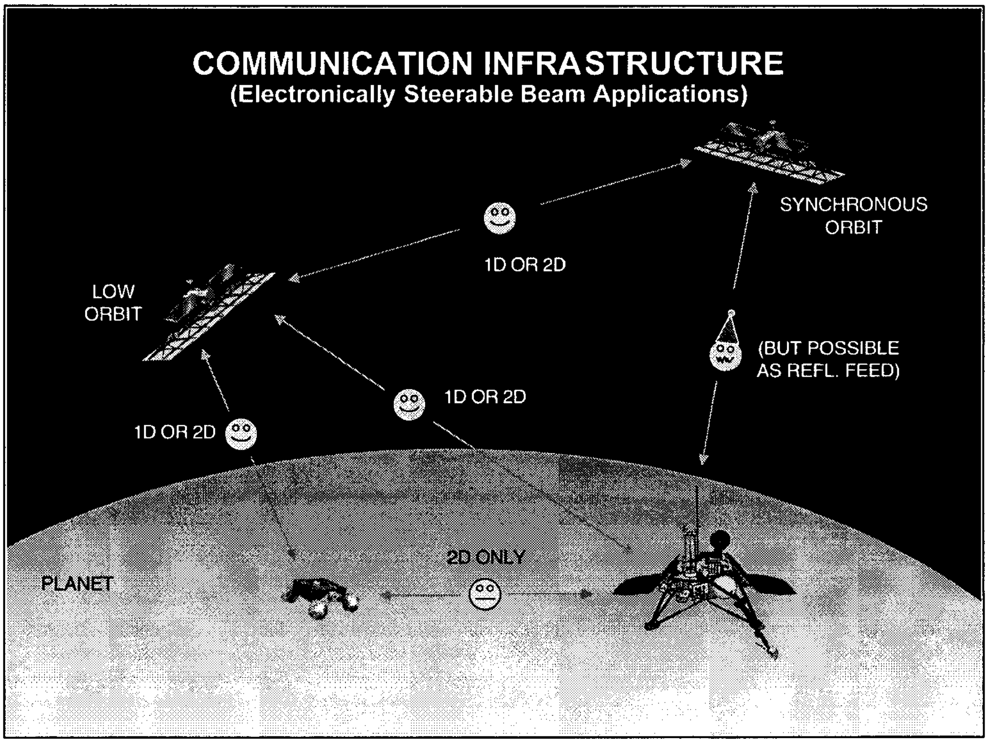
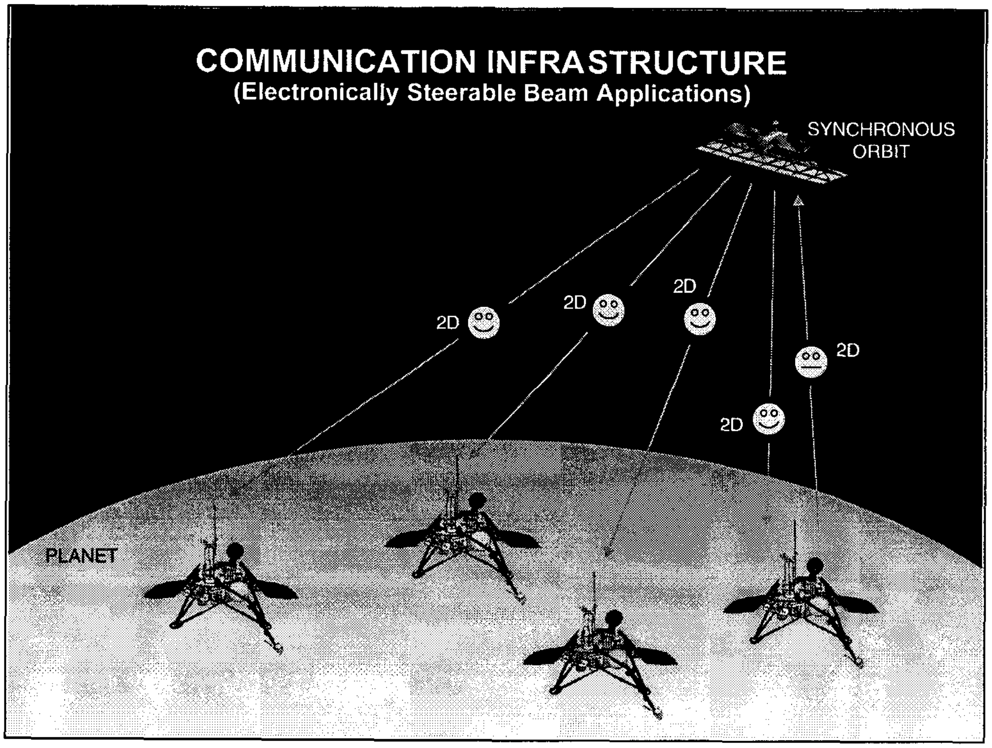
This is a chart similar to the preceding one but, this time computed for two-dimensional apertures. Here again the gain determines the electrical aperture size, the beamwidth, and the number of elements while the frequency determines the physical size of the aperture. Note in particular that a one meter X-Band aperture as well as a 0.3 meter Ka-Band aperture both providing about 40 dB of gain appear to be attractive for planetary use. However, a 50 dB beam even at Ka-Band is probably impractical because of the required number of elements.



So, returning now to the Mars Infrastructure exemplar, we see how such antennas fit into the overall scheme of things. There appears to be no particular advantage to electronic steering in the case of the stationary orbit to fixed lander link. (As indicated, however, an array feed might provide the vernier beam steering need if a large reflector were to produce a beam too narrow to point within the capabilities of the spacecraft attitude control system.) There may be some advantage in the case of fixed lander to rover links but these would probably involve high gain pencil beams rather than the medium gain fan beams produced by one-dimensional apertures. The reason for this is that all beams will have significantly reduced gain near the horizon due to ground absorption of the radiated energy so the higher gain of the pencil beam would probably be needed. However, in all links involving the low orbiter, phased arrays appear to be attractive. Either pencil or fan beams are applicable. In particular, a fan beam from a rover could cover the entire sky with one-dimensional scanning. While electronic speed is not essential, electronic steering seems preferable to mechanical steering from a reliability standpoint.



There is one link scenario in which, while only fixed beams are involved, it appears that the electronic steering of a phased array is desirable. That situation is shown here. The fixed orbiter rapidly sequences among the landers dwelling on each for a time before steering to the next. In this manner a single beam may be used to communicate with a number of landers. Ultimately, such a beam might even be used to both communicate with and locate a set of rovers on the surface. High gain is required for such links because the total data transferred is limited by the dwell time and this dwell time is inversely proportional to the number of landers and/or orbiters to be serviced.

Here again, however, a fully agile beam is of dubious value in the uplink from a fixed lander to a synchronous orbiter.

Conclusions Concerning Phased Arrays for Planetary Exploration

- One dimensional apertures are practically limited to gains of about 20 dB or less.
- Two dimensional apertures are practically limited to gains of about 40 dB or less.
- Electronic speeds are not essential in most planetary applications.
- High gain and (as a consequence) wide angle beam agility are advantageous for short haul links.
- Phased arrays do not appear advantageous for long haul links; i.e., to earth.

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Based on the preceding results, one can reach a number of conclusions outlined here. First, one dimensional aperture phased arrays become impractical at gains greater than about 20 dB primarily due to physical size and number of elements. Two dimensional aperture phased arrays can practically achieve gains up to about 40 dB beyond which the number of elements becomes impractical. In most cases, the configuration of a planetary network changes slowly enough to permit mechanical beam steering but electronic steering still appears to be advantageous from a reliability point of view; i.e., no moving parts. The primary advantage of phased arrays is wide angle beam agility which is, of course, essential to the effective use of the narrow angle high gain beams produced. Finally, long haul links to earth do not benefit from the use of phased arrays primarily due to the limited available gain (40 dB) and the expense of providing beam agility which is not essential to such links.